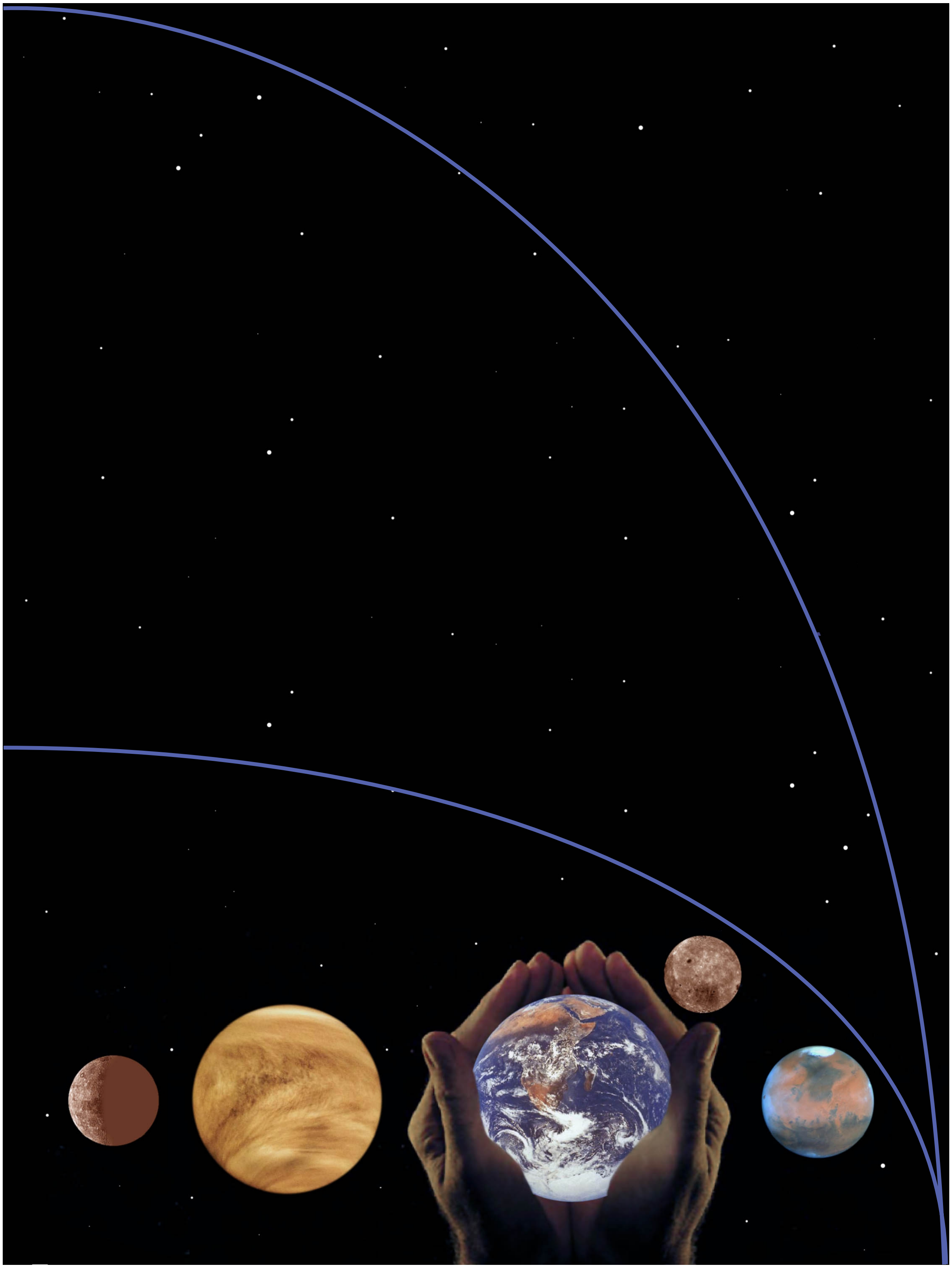

2

Inner Solar System: Key to Habitable Worlds

The inner planets provide a unique opportunity to study the processes that lead to habitable worlds. Venus, Mercury, Mars, and the Moon (Figure 2.1) each hold clues to different aspects of the origin of the planets and habitable environments in the inner solar system. The Moon and Mercury preserve records of past events that are largely erased on Earth and Venus. In many ways, Venus is Earth's twin in the solar system, and it provides a natural laboratory for understanding the evolution of Earth-like planets and their atmospheres, including how Earth's atmosphere might change in the future. Mars shows evidence for substantial climate change, which could reflect processes that influenced all of the inner planets.

UNIFYING THEMES FOR STUDIES OF THE INNER PLANETS

At the most fundamental level, Earth is unique. Through the study of other objects in the inner solar system, it is now understood that Earth as a habitable planet is the result of a series of stochastic events that occurred over its 4.6-billion-year history. The terrestrial or "Earth-like" planets exhibit common geologic processes that both reflect and determine their fate. Each of our neighbors is the result of planetary-scale processes operating in the inner solar system with different boundary conditions.

As the initial reconnaissance of our solar system draws to a close, the scientific goals for exploration are changing. The initial exploratory steps were driven by the intense public and scientific interest in glimpsing new worlds for the first time. As articulated in this report, however, a new paradigm for solar system exploration is emerging, one that seeks to address fundamental questions about our place in the universe. Thus, the unifying themes of the next decade of exploration of the inner planets focus on the following:

- *The past: Where did we come from?* What led to the unique character of our home planet?
- *The present: What is going on?* What common dynamic processes shape Earth-like planets?
- *The future: Where are we going?* What fate awaits Earth's environment and those of the other terrestrial planets?

FIGURE 2.1 *(facing page)* How do the compositions, internal makeup, and geologic history of the planets explain the formation and sustainment of habitable planetary environments? This image shows, from the left, Mercury, Venus, Earth and the Moon, and Mars as they appear in slightly enhanced natural color. Full images of Mercury do not exist. The farside of the Moon is shown. Courtesy of Vesper/Goddard Space Flight Center and Peter Neivert.

Exploration of the inner solar system is vital to understanding how Earth-like planets form and evolve and how habitable planets may arise throughout the galaxy. Understanding processes on a planetary scale—volcanism, tectonism, impact bombardment, evolution of the atmosphere and magnetosphere, and development and evolution of life—requires comparative study of the planets closest to Earth in order to know the effects associated with size, distance from the Sun, composition, and the style of dissipation of internal energy over time. Comparative study of the inner planets shows the importance of a large moon in making Earth unique and perhaps uniquely suitable for life. One of the great advances of geoscience has been to recognize that present-day Earth represents just one step in a progression of changes driven by a complex set of interrelated planetary factors. Coupled with this recognition is the revelation that Earth's atmosphere and biosphere are fragile entities readily perturbed by planetary-scale processes. Much remains to be learned from the other terrestrial planets, where similar processes have produced vastly different results.

In this context, several broad questions that are fundamental to the human quest for understanding our place in the universe can be addressed only by a detailed exploration of the inner planets:

- *Paradigm-altering question.* What geologic and atmospheric processes stabilize climate?
- *Pivotal question.* How have large impacts affected the course of planetary evolution?
- *Foundation question.* How do the compositions, internal makeup, and geologic history of the planets explain the formation and sustainment of habitable planetary environments?

The past four decades of exploration, observation, and research have provided glimpses of Mercury, a first-order understanding of the Earth-Moon system that laid the foundation for much of planetary science, and tantalizing insights into the nature of the atmosphere, surface, and interior of Venus (Figure 2.2). Substantial advances have been made in the exploration of Mars from orbit and at three landing sites for in situ measurements.[a] Clearly, many fundamental questions remain unresolved. Future progress will require detailed study of Earth-like planets and of the constraints on how habitable worlds arise, evolve, and are sustained. The next decade holds immense promise for major advances in answering these questions.

The next three major sections present a broad survey of the state of knowledge of the inner planets in the context of specific scientific issues relating to the themes outlined above. The significance of each issue is explained, and a summary is given of relevant scientific progress to date. Important questions are identified, and future directions for the Solar System Exploration program are then outlined. By their very nature, several of the most fundamental science investigations require commitment to a long-term integrated approach of observation, measurement, and analysis.

WHAT LED TO THE UNIQUE CHARACTER OF OUR HOME PLANET?

The factors leading to Earth's unique characteristics and, by extension, the unique characteristics of the other inner planets may be organized as follows:

- The bulk compositions of the inner planets and their variations with distance from the Sun;
- The internal structure and evolution of the core, crust, and mantle;
- The history and role of early impacts; and
- The history of water and other volatiles and the evolution of inner planets' atmospheres.

Recent progress in studies of each, likely future directions for research, and the important questions that need to be addressed are outlined below.

---

[a]Given the scientific and programmatic importance of Mars exploration, detailed considerations and discussions of the subject are deferred until Chapter 3.

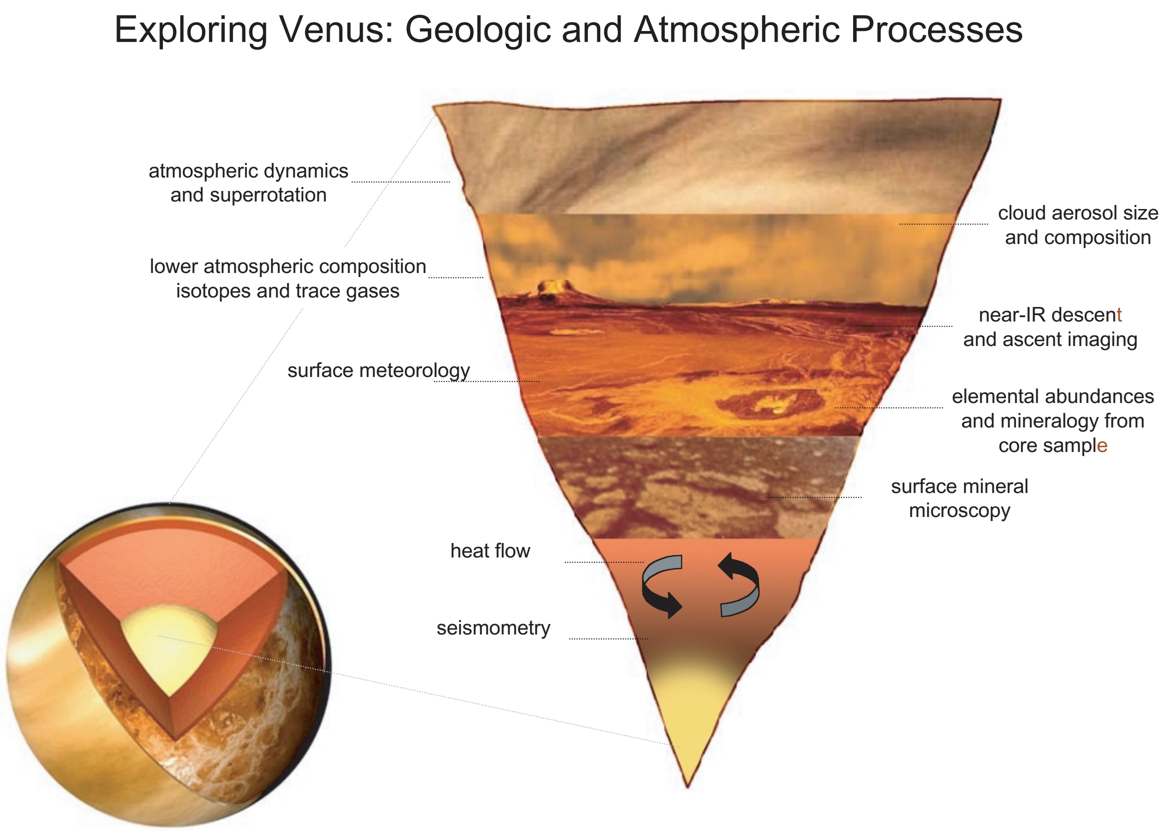

FIGURE 2.2 A slice into Earth's sister planet Venus illustrates the unknown nature of the structure and state of the interior; the composition and history of materials at the surface; and the composition, circulation, and evolution of the atmosphere. Also indicated are some of the means by which these unknowns may be investigated. Courtesy of Jet Propulsion Laboratory, E. Stofan, and M. Bullock.

Bulk Compositions of the Inner Planets and Their Variation with Distance from the Sun

A fundamental constraint on the formation of Earth-like planets is whether the inner planets are random accumulations of specific building blocks or whether a systematic cosmochemical trend related to distance from the Sun exists. The bulk compositions of the inner planets resulted from early nebular processes, planetary accretion, and the removal or addition of material following accretion. The concentrations of volatile elements resulted from primary nebular processes (e.g., condensation), secondary processes (e.g., solar-wind erosion), late addition from comets, or a combination of these processes. Determining the bulk compositions of the terrestrial planets is key to understanding the roles of these major formative processes. Especially important are the noble gases and their isotopes, which record early planetary formation processes because they remain chemically inert.

Recent Progress

Knowledge of bulk compositions has been gleaned from remote sensing, determination of orbital dynamics, and samples of Earth, the Moon, and meteorites (including those from the Moon and Mars). Good progress has been made in determining the surface compositions of the Moon, of some asteroids, and, to some extent, of Mars and Mercury. In situ measurements for Venus, made at seven locations by (short-lived) landed Soviet missions, suggest basaltic and alkaline surfaces. However, the bulk composition remains poorly known. Synthesis of these results suggests that although some rock-forming elements occur in the inner solar system in chondritic relative proportions, the volatile elements are depleted.[1] Indeed, compositions of planetary basalt suites possibly reflect a gradient in the abundance of volatile elements, increasing with distance from the Sun.

Isotopic data on oxygen, hydrogen, and other volatiles provide clues to planetary compositions, their atmospheres, and early solar system processes and environments relevant to the origin of life. Isotopic data from Earth and Mars suggest that primary atmospheres were lost and later replaced by volcanic outgassing or addition from comets.[2] The (incomplete) measurements of the atmosphere of Venus are consistent with solar values and could reflect the influence of a primordial atmosphere, but the state of chemical and isotopic equilibrium of the surface and atmosphere is unknown. Each of the inner planets has a complex history of postaccretional processes that have contributed to and modified its surface and atmospheric compositions. Analysis of diverse surface materials, determination of their ages, and assessment of the processes that have affected them are needed in order to understand how volatile-element contents have evolved differently on each of the planets.

Future Directions

- *Mercury.* Basic information is needed on surface composition, internal structure, and distribution of mass, each of which provides important constraints on bulk major-element composition.
- *Venus.* Compositional measurements of the surface and the atmosphere (especially the noble gases) are needed in order to understand the bulk composition and the origin of Venus's atmosphere. Oxygen isotopic ratios would provide key geochemical constraints on the planet's composition for understanding differences among the inner planets and for testing models of formation. Measurements of the chemical state of the surface and near-surface environment are needed to understand surface and atmosphere interactions.
- *Moon.* Seismic data would resolve the internal structure, permitting a much-improved estimate of bulk composition. Samples of rocks from major unsampled terrains, primarily the South Pole-Aitken Basin, are needed to determine an accurate deep crustal composition and stratigraphy.

Important Questions

High-priority investigations relating to bulk compositions of the inner planets and their variation with distance from the Sun are as follows:

- Determine elemental and mineralogical surface compositions,
- Determine noble gas compositions of atmospheres,
- Determine oxygen isotopic compositions of the unaltered surface and atmosphere, and
- Determine interior (mantle) compositions.

Internal Structure and Evolution of the Core, Crust, and Mantle

Knowledge of the internal structure of the planets is fundamental to understanding their history after accretion. Key issues include dissipation of internal heat, core formation and associated issues concerning magnetic-field generation, distribution of heat-producing radioactive elements, and styles and extent of volcanism. Earth's crust is the product of differentiation and several billion years of recycling through plate tectonics, with water being a critical ingredient.

Mercury is small, and its ancient surface suggests a lack of crustal recycling or extensive resurfacing. Although models suggest that the silicate portion of Mercury differentiated to form a crust and mantle, little is known about its crust-mantle structure or composition. Similarly, recent results suggest that Mars probably has a mantle and core, but the interpretation is model-dependent. Based on analysis of lunar samples, the Moon began hot, with an ocean of magma some 400 km deep; its crust was extracted as the low-density component during solidification of the magma ocean, but insufficient heat remained to recycle material. Venus, on the other hand, has been geologically active within the past billion years, yet its surface is very different from Earth's and exhibits no similar plate tectonics. Processes of crustal formation and the dynamics of mantle movements are poorly constrained.

Recent Progress

Knowledge of the internal structure of the Moon is constrained by samples, limited on-surface geophysical measurements, and data from orbit. Results indicate a differentiated low-density, aluminosilicate crust of about 40 km to 100 km, overlying a ferromagnesian silicate upper mantle,[3,4] and a small iron-rich core.[5] Remote-sensing data show that the Moon has a strong hemispheric asymmetry. What caused the asymmetry is not known, but it is likely that it influenced the distribution and extent of subsequent volcanism. The topography of Mars also shows a dichotomy between the northern lowlands and the southern cratered highlands. Although several hypotheses have been posed to explain the dichotomy, including those related to both internal and external processes, these ideas remain untested.

Venus's topography is known from Pioneer Venus and Magellan measurements and, although these data reveal extensive tectonism and volcanism, the expressions of Earth-like plate tectonics are absent. Instead, topography and the relative youth of the Venusian surface indicate a major, possibly global, resurfacing that may have occurred episodically.[6,7] Although Venus appears to have an iron core, the absence of a magnetic field suggests that it does not have a magnetic dynamo, perhaps consistent with its slow rotation. Limited Mariner 10 data at Mercury indicate the presence of a magnetic field with a magnetosphere capable of standing off the solar wind most of the time. It is possible that a dynamo or a strong remnant magnetic field is present. Either way, Mercury's large metal core plays a key role. Whether Mercury and Venus have solid inner cores and liquid outer cores is not known.

Future Directions

Seismic data for each of the inner planets are ultimately needed to constrain the structure, mineralogy, and composition of the deep planetary interiors. Key investigations that address evolution of the crust, mantle, and core include the following:

- Determination of the horizontal and vertical variations in internal structures,
- Determination of the compositional variations and evolution of crusts and mantles,
- Determination of the major heat-loss mechanisms and resulting changes in tectonic and volcanic styles, and
- Determination of the major characteristics of iron-rich metallic cores (size and the nature of liquid and solid components).

The History and Role of Early Impacts

An early paradigm shift in the understanding of the solar system was the realization that impacts constitute a fundamental process, particularly in early planetary formation. For example, current understanding suggests that proto-Earth was struck by a Mars-size object, resulting in the formation of the Moon and setting Earth on a distinctive evolutionary path. Impact-generated heating likely caused partial to global melting of the terrestrial planets, leading to the formation of magma oceans and differentiation of the interior.

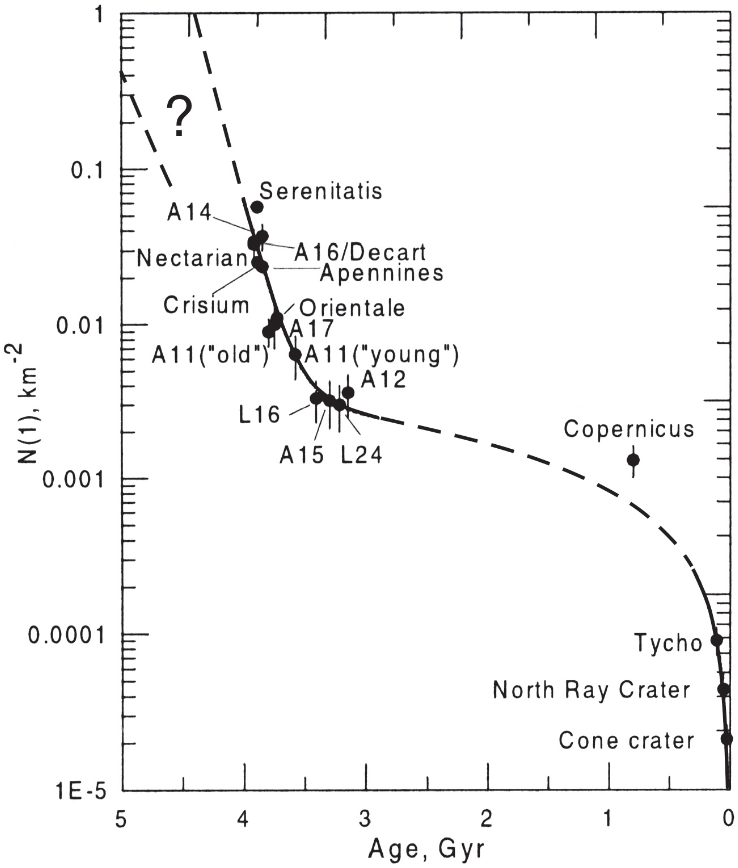

FIGURE 2.3 Cumulative crater frequencies (i.e., the number of craters equal to and larger than 1 km in diameter per square kilometer) with time, as derived from lunar surfaces dated from returned samples. Crater frequency data are then used to estimate the age of unknown planetary surfaces. The recent crater flux at 1 AU is partially constrained by terrestrial craters, but the period prior to 4.0 billion years is unknown. The apparent cluster of basin-forming events near 3.9 billion years is particularly puzzling and has several implications for early solar system history. Adapted from G. Neukum, B.A. Ivanov, and W.K. Hartmann, "Cratering Records in the Inner Solar System in Relation to the Lunar Reference System," *Space Science Reviews* 96: 55-86, 2001.

Large, early impacts played a key role in establishing the structure of the early crust, which remains exposed on the Moon, Mars, and the observed part of Mercury. This structure influenced subsequent surface and near-surface evolution, such as the emplacement of lunar lava flows. However, because data are incomplete, it is not known if global melting and differentiation occurred on all of the terrestrial planets, or if impact basins dominate the crustal structure of Mercury as they do on the Moon and to some extent on Mars. The history of volatiles and planetary atmospheres were also affected by impacts, both through implantation by comets and removal of gases through impact erosion.

The lunar impact record, dated by samples, is used to extrapolate surface ages throughout the solar system. However, there is considerable uncertainty in the early flux of impacts, with two models proposed. In one, the flux decayed exponentially with time; in the other, the flux peaked at about 4 billion years (Figure 2.3).[8] Because the lunar cratering record is used for dating events throughout the solar system, resolving the lunar cratering record is key.

Recent Progress

Only half of Mercury's surface has been seen and, while the Magellan mission provided global reconnaissance of Venus, it is not known if vestiges of early crust remain there. The paucity of impact craters on Venus suggests a relatively youthful surface. However, estimates of surface ages are poorly constrained, ranging from <250 million years to nearly a billion years old.[9] Samples from nine locations on the Moon enable dating of key events in lunar evolution, but the chronology of most large, early impactors is poorly known.

Future Directions

Understanding the role of early impacts requires age-dating key terrains on the Moon and Mercury, mapping all of Mercury, and obtaining compositional, mineralogical, and petrologic measurements of key terrains on the terrestrial planets. The following specific investigations need to be conducted:

- Determination of large-impactor flux in the early solar system and calibration of the lunar impact record,
- Determination of the global geology of the inner planets, and
- Investigation of how major impacts early in a planet's history can alter its evolution and orbital dynamics.

The History of Water and Other Volatiles and Evolution of the Inner Planets' Atmospheres

An accurate account of the history of water and other volatile compounds is essential for understanding the origins of the environments of the inner planets. Planetary atmospheres have been severely affected by processes that occurred after planetary formation, including internal processes (e.g., volcanism) and external processes (e.g., impact and late-stage accretion), but the data are insufficient to determine the exact evolutionary paths. Accurate measurements of hydrogen and isotopic abundances of noble gases and oxygen in the atmosphere, soil, and rocks are required. These data are necessary to determine the fraction of pristine, nebular volatiles versus later cometary-impact volatiles and to understand the loss rates of atmospheres in the early phases of planetary formation.

Recent Progress

The Moon and Mercury may have yet undetected significant species in their tenuous atmospheres.[10] At Mercury, coherent radar backscatter indicates volatiles at high latitudes.[11] Clementine data suggest buried water ice at the lunar south pole, while Lunar Prospector detected significant quantities of hydrogen at both poles, but the form, extent, and origin of such deposits are not known. Although volatiles are strongly depleted in the Moon's crust, the volatile content of the deep interior is poorly constrained. Mars also exhibits significant amounts of hydrogen in the polar regions. On the other hand, solar-wind implantation deposits hydrogen and helium in the lunar regolith. The principal volatile constituents of Venus and Mars are known.[12,13]

Much is known about the mechanisms of atmospheric loss—Jeans escape, hydrodynamic escape, exospheric sputtering, and solar-wind sweeping are the main processes. Application of these processes to Earth, Mars, and Venus is used to infer the past and present states of the atmospheres, particularly regarding the loss of water vapor.[14] For Mars and Venus, photochemical and other predictions of less abundant species exist, but no actual detections of them have been made.

Future Directions

Water and the volatile compounds that make up the atmospheres of the inner planets are also partitioned among the interiors, crusts, and hydrospheres of these planets. The evolution of water and volatiles since our solar system's formation is central to an understanding of terrestrial planets' evolution to either support life or prevent its inception. An exploration program that includes the following will achieve this new understanding:

- High-precision measurements of noble gases and light stable isotopes,
- Determination of the composition of magmatic volatiles, and
- Determination of the composition and source of the polar deposits on Mercury and the Moon.

WHAT COMMON DYNAMIC PROCESSES SHAPE EARTH-LIKE PLANETS?

The dynamical influences shaping Earth-like planets include the following:

- Processes that stabilize climate,
- Active internal processes that shape the atmosphere and surface environment, and
- Active external processes that shape the atmosphere and surface environment.

Recent progress in studies of each, likely future directions for research, and important questions that need to be addressed are outlined below.

Processes That Stabilize Climate

Venus, Earth, and Mars have complex interactions between the surface, atmosphere, and interior. Mars is most likely geologically quiescent, although because of variations in its motion around the Sun, it experiences changes in solar energy input and thus in cycles of water and carbon dioxide between polar caps, surface, and atmosphere. The connections between these environments on Mars and Venus are manifestly different from those on Earth. Looking and thinking beyond Earth's climate system will enable us to more deeply understand processes that affect climate and how they interact in establishing planetary environments. Understanding the factors influencing plate tectonics (initial planetary composition, internal dynamics, and the role of water) is of prime importance in understanding the stability of climate. The effects of clouds, volcanism, and tectonism on climate stability are also important but not well understood. Studies of the Moon and its formation are important to understanding how astronomical perturbations affect climate on terrestrial planets.

Recent Progress

Comparative studies of the surfaces, atmospheres, and interiors of the inner planets show that, while common physical processes operate on these planets, their interactions and collective effects are expressed differently.[15] On Earth, plate tectonics recycles crustal material and cools the interior. Carbon, oxygen, sulfur, and nitrogen cycle among the atmosphere, biosphere, oceans, crust, and interior. Earth's Moon helps stabilize obliquity and therefore seasonal variations.[16] Although Mars and Venus have their own, unique versions of volatile cycling, neither of them currently has plate tectonics or moons that affect their orbital stability.

Future Directions

Critical interactions between the interior and atmosphere of Venus are not understood. Science investigations central to understanding climate should do the following:

- Determine the general circulation and dynamics of the inner planet's atmospheres;
- Determine the composition of the atmospheres of the inner planets, especially trace gases and their isotopes;
- Determine how sunlight, thermal radiation, and clouds drive greenhouse effects; and
- Determine processes and rates of surface/atmosphere interaction.

Active Internal Processes That Shape the Atmosphere and Surface Environments

Processes taking place within a planet—including volcanic outgassing, generation of magnetic fields, and exchange or recycling between the surface, atmosphere, and interior—affect the current state of the surface and atmosphere. For example, prolonged volcanic eruptions can affect climate and atmospheric evolution. The magnetic field of a planet recycles ions back into the atmosphere and protects it from solar-wind erosion. Magnetic fields are generated by internal processes, most likely from an internal dynamo driven by differential rotation of a solid inner and liquid outer core. What would Earth currently be like without plate tectonics or without its protective magnetic field? The lack of plate tectonics on the other terrestrial planets, the lack of a magnetic field at Venus and the weak field at Mercury, and the remnant magnetization of Mars allow us to explore "alternative scenarios" for the current state of processes active on Earth and to understand the relative significance of the interplay between volcanic activity and atmospheric composition in generating and sustaining habitable environments.

Recent Progress

The hot interiors of planets drive tectonic and volcanic processes such as plate tectonics. Volcanic activity on the Moon and Mercury occurred early, activity on Mars extended longer, while Earth and probably Venus remain geologically active. On all of the inner planets, active internal processes contributed to their atmospheres through outgassing and, on most bodies, interactions continue between the surface and the atmosphere. Venus, the only other inner planet likely to still have a dynamic interior, lacks plate tectonics, and the evolution of its interior is a subject of much debate.[17] The rates of tectonic and volcanic activity are not quantified for Venus, and the ages of major surface units that would help constrain rates of volcanism cannot be determined from remotely sensed data.

Earth has a strong, dipolar magnetic field that stands off the solar wind. Mariner 10 data showed that Mercury has a dipolar field, aligned in the same sense as that of Earth and with 0.001 of its surface field strength.[18] Although the Moon has remnant crustal magnetism and anomalies, their source is not clearly understood. Recent results from the Mars Global Surveyor spacecraft indicate that Mars has remnant magnetism,[19] suggesting the possibility that a magnetic field once existed, enabling a thicker atmosphere.[20] Venus has no measurable magnetic field, although it is not known if one existed in the past.

On Earth, the lithosphere, hydrosphere, biosphere, and atmosphere participate in the cycling of volatiles such as water and carbon dioxide. The current lack of a hydrosphere and biosphere on Venus provides a unique opportunity to analyze the links between processes in the interior, volcanic activity, composition of the surface and atmosphere, generation and maintenance of the global cloud layer, and chemical weathering of the surface. Key steps include measuring the following: the composition of the lower atmosphere, isotopic noble gas abundances in the atmosphere, mineralogy and composition of surface rocks, and the rates of active processes on Venus by accurately dating key surfaces.

Future Directions

Knowledge of the current state of internal geologic activity as well as the state of evolution of the surface and of past or present magnetic fields is needed in order to characterize active processes on the inner planets. The highest-priority measurements are these:

- Characterize current volcanic and/or tectonic activity and outgassing;
- Determine absolute ages of surfaces; and
- Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium.

Active External Processes That Shape the Atmosphere and Surface Environments

The inner planets share a common environment in our solar system in which active processes such as solar-wind bombardment affect how the atmospheres and surfaces evolve. Because the inner planets are close to the Sun, a common loss process for their atmospheres is solar-wind sweeping, in which ionized species are removed from the top of exospheres by electric fields connected to the interplanetary medium. Magnetospheres can help recycle ions into the neutral atmosphere, but the efficiency of this process is unknown. Studies of the effects of the solar wind on planets with weak or no magnetic fields provide a basis for understanding how external processes affect atmospheric evolution.

Micrometeorite bombardment modifies the surfaces of Mercury and the Moon and injects material into their exospheres. Bombardment by larger objects is more infrequent, but it radically changes the surfaces and atmospheres over time. Cosmic rays, meteorites, ion bombardments, and implantation alter the structure of the uppermost regoliths of Mercury and the Moon. The same processes comminute, vaporize, and mix the regolith while adding exogenous material. These external processes affect each of the inner planets in different ways and at different scales, changing their surfaces and atmospheres in ways that determine how habitable environments are maintained.

Recent Progress

Pioneer Venus measured the radiation and particle environment for 14 years, resulting in our knowledge of the effects of external processes on the planet's upper atmosphere. The extent to which the lower atmosphere and surface are perturbed by external processes is not known but is thought to be minor because of the dense atmosphere. One exception could be deposition of volatiles by cometary impact. A better characterization of the escape rates of various species from the atmosphere of Venus will aid in an understanding of how that planet's atmosphere has evolved.

Mercury's dipolar magnetic field is believed to stand off the solar wind much of the time. The tenuous surface-bounded atmospheres of Mercury and the Moon are a result of meteoritic impact volatilization of both the surface and the impactor (sodium, potassium, and calcium) and solar-wind-implanted hydrogen and helium.[21] The origin of high-latitude trapped lunar and mercurian volatiles is currently a matter of intense discussion.

The combined effects of small-scale processes that mobilize and alter the surface on airless bodies have recently been recognized through detailed analysis of lunar soils enabled by improved instrumentation in Earth-based laboratories.[22,23] The nature and rate of such processes are still unknown.

Future Directions

Several investigations are important for understanding external processes active in the inner solar system. They should do the following:

- Make precise compositional measurements of the surface-bounded atmospheres of Mercury and the Moon and determine the relationship between ionospheres and magnetospheres,
- Quantify processes in the uppermost atmospheres of the terrestrial planets, and
- Quantify regolith processes on bodies with tenuous atmospheres.

WHAT FATE AWAITS EARTH'S ENVIRONMENT AND THOSE OF THE OTHER TERRESTRIAL PLANETS?

Discussion of the fate of Earth's environment and those of the other terrestrial planets is organized under the following headings:

- The vulnerability of Earth's environment as revealed by the diverse climates of the inner planets,
- The varied geological histories of the inner planets that enable predictions of volcanic and tectonic activity,
- The consequences of impacting particles and large objects, and
- The resources of the inner solar system.

Recent progress in studies relating to each of these factors, together with likely future directions for research, are outlined below.

Vulnerability of Earth's Environment As Revealed by the Diverse Climates of the Inner Planets

Mars is a small, frozen world, hostile to life because of its thin atmosphere and harsh radiation environment. Venus has a dense atmosphere that traps radiation so efficiently that its surface is as hot as an oven; the atmosphere is 10 percent of the mass of Earth's ocean and is a supercritical fluid at the surface. Given these two extremes and the awareness that humans are altering Earth's climate, what is the fate of Earth's environment? Can we inadvertently cause Earth to evolve to states similar to that of either Mars or Venus or some other inhospitable regime? To answer this question requires investigating the geochemical cycles that affect climate by determining the composition of the lower atmosphere and surface of Venus, how its atmosphere evolved to its present state, and how atmospheric loss processes affect bulk properties of the atmosphere and surface of terrestrial planets.

Recent Progress

Earth's climate record illustrates that there are wide swings in regional and globally averaged surface temperatures.[24,25] Mars once had liquid water on its surface, when the Sun's luminosity was less than it is today.[26] Evidence indicates that Venus's climate has varied significantly in the past billion years.[27] It is now known that terrestrial planetary environments are maintained by complex interactions among the surface, atmosphere, and interior. The physical states of the terrestrial planet environments have been the focus of exploration, including the photochemistry of Venus's clouds and the role of early volcanism on Mars. However, how these processes establish and maintain climate is poorly understood.

Future Directions

Global monitoring of Venus's atmosphere and climate; in situ elemental, mineralogical, and geochemical measurements of the planet's surface; and detailed data on the noble gas isotopes and trace gas abundances of the atmosphere are necessary in order to understand terrestrial planet climates. This should also include characterizing the geochemical cycles of sulfur, hydrogen, oxygen, nitrogen, and carbon. The most important investigation is the following:

- Characterize the greenhouse effect through meteorological observations.

Varied Geologic Histories That Enable Predictions of Volcanic and Tectonic Activity

Volcanism and tectonism reflect the release of heat from planetary interiors. These processes have operated throughout the history of Earth and will probably continue in the future. Manifested through volcanic activity and earthquakes, these processes have an enormous influence on society.

The inner planets all have indications of resurfacing by volcanism and crustal disruptions by tectonic processes. Although the timing and style of these processes vary among the planets, they provide clues to the evolution of planetary interiors and insight into possible future geologic activity. For example, volcanism on the Moon appears to span a wide range of time, but it decreased substantially in the last third of the Moon's history. In contrast, volcanic and tectonic activity on Venus has been extensive throughout its "visible" history, and the planet could be currently active. These two cases reflect (in part) the relative sizes of the bodies, in which internal activity extends over a length of time that scales with planetary diameter. Mercury's volcanic history is not known, although the impact record suggests an ancient surface, relatively unaffected by volcanism.

Although on Earth tectonism is manifested globally through plate motions, knowledge of the styles and history of tectonic deformation on all terrestrial planets is required in order to understand the general process and, thus, the behavior observed on Earth.

Recent Progress

Global mapping of Venus by the Magellan radar mission revealed a surface estimated to be less than 1 billion years old. The current explanation suggests that extensive "overturning" of the lithosphere resulted in near-global resurfacing. Although similar in size and composition to Earth, Venus does not appear to have plate tectonics. However, as on Earth, recent activity may be detectable in measurements in Venus's atmosphere and clouds through monitoring reactive volcanic gases (e.g., hydrogen chloride, hydrogen sulfide, and sulfur dioxide) or derived aerosols.

The Moon and Mercury have very different histories compared with those of Venus and Earth. The surface of Mercury has probably been modified by contraction associated with the cooling of its large iron core and possibly from stresses associated with the slowing of its spin rate over time, but the extent of volcanism is unknown.

Although it is not known when volcanism began on the Moon, evidence suggests that it was common prior to the last major basin-forming events (~3.8 billion years ago) and ceased much later, at about 2 billion years ago.[28]

Future Directions

A deeper understanding of how volcanism and tectonism vary over time and across planetary surfaces requires determining the current interior configurations and the evolution of the surface expressions of volcanism and tectonism. An understanding of the rates and chemistry of recent volcanism is necessary in order to make connections between geology and climate change. Specific recommendations are these:

- Assess the distribution and age of volcanism on the terrestrial planets, and
- Search for evidence of volcanic gases in inner-planet atmospheres.

Consequences of Impacting Particles and Large Objects

Collision between solar system bodies is a fundamental process, with enormous consequences for the formation, destruction, and sustainment of habitable environments. On Earth, the demise of the dinosaurs and other species exemplifies a process that has likely occurred numerous times on Earth. As currently understood, impact cratering was frequent following planetary accretion, and it declined sharply between 3 billion and 4 billion years ago. However, perturbations in the more recent impact flux and causes thereof and the identity of the impacting objects remain poorly known. In addition, a constant flux of interplanetary particles and ions impact the planets, interacting with their atmospheres and surfaces. Continuing to develop our understanding of the origins of the impactors and the factors affecting the flux should lead to a predictive capability and an improved understanding of links to human and other biological activities.

Recent Progress

The rates and history of impact cratering of the Earth-Moon system are understood through precise ages of lunar samples and documented impact craters on Earth. Since about 3 billion years ago, the average cratering rate on the Moon has been similar to that of Earth, and the rates are roughly consistent with those estimated from the present near-Earth flux of asteroids and comets.[29] Cratering rates, however, have probably not been constant, but have responded to fluctuations related to breakup of main belt asteroids, tidal disruption of comets passing close to

Jupiter, and perturbation of comets from the Oort cloud resulting from galactic tidal forces or gravitational pulses from passing stars or other concentrations of mass.

Future Directions

The continued discovery of craters in Earth's geologic record and future dating of materials on the inner planets will allow the definition of flux variations and the identification of impactors and causes of variability. The surfaces of Mercury and the Moon potentially provide the history of solar-wind activity in the inner solar system. In this case, the past holds the key to the future, and the past record is well preserved on the Moon and Mercury. Specific investigations should include the following efforts:

- Determine the recent cratering history and current flux of impactors in the inner solar system, and
- Evaluate the temporal storage and record of solar-wind gases.

Resources of the Inner Solar System

A basic component of planetary exploration is to characterize surface materials; in so doing, resources may be identified that have practical and economic use either in space or on Earth. In the absence of water and with the crustal recycling on Venus, Mercury, and Mars, ore resources may prove rare. Nonetheless, future exploration of these planets may reveal unexpected geological resources. In the near term, however, the only feasible resources of the inner planets are those of the Moon. Such resources are likely to play a prominent role in long-term exploration of the solar system by humans.

Recent Progress

Although the Moon is depleted of volatile elements, enrichments occur at the surface: (1) at the lunar poles, where hydrogen and perhaps other volatile species, possibly delivered by cometary or other volatile-rich impactors, have been trapped in cold, permanently shaded craters; and (2) in ordinary surface regolith, owing to implantation of solar wind.[30] The potential production of propellant is significant, because development costs for heavy lift launchers are high and have been viewed as stumbling blocks for planetary exploration strategies. The isotope ^{3}He is a potential clean fuel that is rare on Earth but is concentrated by the solar wind in lunar regolith.[31] Bulk construction materials are available, including metals such as iron and aluminum; ceramics; glasses; and sintered regolith, for a lunar variety of concrete, given a ready supply of water. Except for the polar deposits, most of the Moon's resources are well understood and await technology development for use.

Characterization of potential resources, especially confirmation of polar hydrogen deposits and determination of mineral/chemical form, is needed. Operation in the extreme cold of permanently shaded craters is a technical challenge that also needs to be addressed. Concentrations of materials may exist that some have argued are of economic interest, such as ^{3}He in lunar regolith. Such deposits may be identified through surface geochemical surveys and the analysis of samples of surface regolith and rocks. Geochemical indicators of ore processes may be subtle or minor; thus, sample return and analysis have the best likelihood of discovering such processes. In situ analyses, especially of the physical and geotechnical properties of the surface, are needed in order to proceed with mining and materials processing.

Future Directions

The next steps in determining which, if any, inner solar system materials may enable future human exploration activities include the following:

- Assess volatile resources, and
- Assess mineral resources.

INTERCONNECTIONS

Links to Astrobiology

Astrobiology is an integrating theme that provides a common thread for understanding planetary habitability and addresses some of the most exciting intellectual questions of our time, such as the nature of life and the existence of habitable worlds. Astrobiology not only includes the search for extant or extinct life, but also seeks to define the conditions that lead to habitable planetary environments and to discover whether the characteristics of our system that allow life to exist here are likely to be common or rare in the galaxy.

The terrestrial planets provide insights into the conditions that might have been favorable for organic evolution. A deeper understanding of the origin and evolution of volatiles, impact history, and their implications for composition and habitability is crucial. The astrobiology community recognizes the need for study of Venus in order to understand the implications of the differences between the evolutionary paths taken by Venus and Earth. Exploration of the inner planets must now include more detailed in situ experiments that characterize the mineralogy, geochemistry, and time-variable processes that occur on the surface. More detailed measurements of planetary atmospheres are needed in order to understand the general principles that drive climate. Most importantly, samples from the Moon, Mars, Venus, and Mercury must be returned to Earth's laboratories for exhaustive study. Only then will we approach an integrative understanding of the terrestrial planets so that we can answer the questions of what led to the uniqueness of our home world, what common dynamic processes shape Earth-like planets, and what the fate of terrestrial planetary atmospheres is.

Links with Mars

The program of exploration at Mars is motivated by the possibility that conditions favorable for life may have existed there in the past. Data from Mars missions are critical to address some of the questions for the inner planets outlined above. However, to understand the range of conditions that lead to habitable environments, measurements need to be made at Mercury, Venus, and the Moon that will maximize the science return from the Mars program.

The strategy for Mars exploration combines remote sensing, measurements made on the surface, and the return of samples to Earth from well-characterized localities on Mars. Because the cost of sample-return missions from Mars is high, emphasis has been on remote-sensing and landed missions that enable the identification of critical places from which the samples would be returned, consistent with the overall science objectives. At the same time, it is recognized that well-documented samples from nearly any site that is relatively well understood will provide an enormous advance in our understanding of Mars. The panel's strategy for the exploration of the other inner planets follows a similar path, leading to the return of samples to Earth. As outlined in the previous sections, samples afford the means to test specific hypotheses posed from orbital and lander missions. Most importantly, they provide data that cannot be otherwise obtained, such as radiometric ages for key surfaces and identification of isotopic and trace-element signatures of planetary formation and evolution processes.

Within the priorities set by NASA's Mars Exploration Program, not all aspects of Mars science will be completed in the core program. Thus, the Mars Scout Program, patterned on principal-investigator-led Discovery missions, is incorporated to provide flexibility in the exploration of Mars. Similarly, many aspects of the inner planets can be addressed by Discovery-class projects to respond to new findings, instruments, or approaches.

Links with Primitive Bodies

Small bodies (asteroids, comets, and Kuiper Belt objects) are considered to be remnants of the original "building blocks" of the solar system. The main belt of asteroids between Mars and Jupiter contains a range of small planetary bodies—some with diameters comparable to those of Pluto and Charon and some only meters across. Planetary accretion that continued elsewhere to form the inner planets was halted in this part of the solar system because of the growth of Jupiter.[32] Main belt asteroids thus appear to represent an early, but interrupted, state of planet formation.[33] Among the asteroids, several rocky bodies have achieved a size comparable to that of small planets; in at least one case (Vesta) early forms of internal processes common to the inner planets (such as differentiation and volcanism) had begun.[34,35] Many of the questions posed above are directly relevant to the large asteroids and argue for detailed exploration. Meteorite samples studied in Earth-based laboratories provide invaluable constraints on the composition of such primitive materials of the solar system. Yet not only is the link between meteorites and individual asteroids poorly known, but it is also clear that we do not have fully representative samples of the important building blocks. Systematic sampling of small bodies of the solar system is complementary to the high priority given to obtaining samples from each of the inner planets.

KEY TECHNOLOGIES, SUPPORTING RESEARCH, AND FACILITIES

Technology

In the next phase of exploration, access to the surfaces and atmospheres of the inner planets is required in order to address fundamental science questions. Without the development of enabling technologies, missions to the surfaces of planets with extreme environments, such as Venus and Mercury, are not possible. Enabling technologies are also necessary for sample-return missions to these bodies, which in turn are essential to answering some of the paradigm-altering questions described above. Enabling technologies include extreme temperature (hot and cold) survivability systems, sample transfer from surface to orbit, shallow drilling and sample handling capabilities, high-temperature balloon materials, long-lived and compact power sources, and surface and atmosphere mobility.

Contributing technologies for inner-planet missions help to reduce mission cost and increase capabilities. Contributing technologies include advanced in situ instrument technologies (including radiometric age-dating and chemical and mineralogical analysis), improved communication technologies, advanced propulsion, autonomous entry, descent and landing and hazard-avoidance software to reduce risk, and overall reductions in mass in order to maximize science return. For the Moon, a relay satellite would enable communications with and control of robotic assets (e.g., rovers and geophysical networks) on the farside.

Many of the enabling technologies can be developed and tested on Earth, while some require technology demonstration flights. The panel strongly advocates missions that both provide science results and validate technologies for future science missions.

Supporting Research and Analysis

A robust research and analysis (R&A) program is absolutely essential for maximizing the science return from missions to the inner planets. It is important that a broader range of research be conducted than is represented by the focused mission set implemented during the next decade. This integrated R&A approach should involve the full science community in harvesting the widest range of science return. A strong R&A program is necessary to stimulate science discussion and to lay a foundation for planning missions in subsequent decades. Laboratory spectroscopy, rock and soil experiments, tests in planetary environmental chambers, theoretical analyses, field studies, and detailed sample studies must occur in parallel with space missions. Many concepts and hypotheses associated with planetary exploration can be tested or evaluated using Earth-based laboratory or analog studies. Data gathered by each mission must be evaluated in the context of existing knowledge and integrated with other observations. Typically, the analysis of data from a specific mission extends years beyond the initial processing and release of data, and with each new data set, reevaluation of the older data sets is extremely important. Such studies require sustained and stable programmatic support to harvest and extend the scientific return on exploration missions.

Earth-Based Telescopes

Ground-based telescopes should be supported for robust planetary programs that deliver new discoveries (e.g., the Na, K, and Ca atmosphere at Mercury; SO_2 and other trace gases in Venus's atmosphere, and O_2 in

Mars's atmosphere) and supporting science (for example, association of Na and K with surface features at Mercury, studies of deep thermal emission and water vapor clouds, mineralogic mapping, and monitoring of seasonal and daily water vapor at Mars). Much of this work is done with small telescopes in the 1.5- to 4-m class, which are threatened in a period of building very large (8-m and greater) astronomical facilities for deep-sky exploration. In addition, the new airborne observatory SOFIA (Stratospheric Observatory for Infrared Astronomy) will be a significant resource for exploration of the inner solar system, especially for spectroscopy of Mercury and the Moon and isotopic studies of the atmospheres of Venus and Mars. These facilities should be kept available for synoptic monitoring of inner-planet atmospheres (e.g., SO_2 and other molecular species at Venus, water at Mars, and Na and K at Mercury and the Moon). The planetary radar facility at Arecibo observatory should also be available for inner-planet studies, especially for Mercury.

Sample Curation and Laboratory Facilities

An integral part of the exploration of the inner planets includes the return of multiple samples from key planetary terrains, as well as atmospheric samples from Venus. The return of samples requires detailed planning and the implementation of appropriate facilities and protocols to receive the samples, enable initial analysis, and distribute the samples to the scientific community, all consistent with issues such as planetary protection. Such samples will most likely be very small and unique, thus requiring the development of specialized equipment and procedures. Although some of this infrastructure will be in place through the Mars Exploration Program, provisions must be made to accommodate the full spectrum of potential materials returned from the inner planets.

RECOMMENDATIONS OF THE INNER PLANETS PANEL TO THE STEERING GROUP

Detailed exploration of the inner planets is crucial for developing the necessary understanding about the uniqueness of the planet on which we live and the knowledge that can affect the future of this planet. Much highly significant science can and should be accomplished in the next decade.

After a careful evaluation of numerous near-term mission options for the inner planets, two missions stand out as providing the most abundant and highest-priority science. Both are medium-class missions. Although large missions to the inner planets are feasible and would certainly be of enormous value, the Inner Planets Panel thinks that the timing of these two priority missions and the investment made would be well tuned to the current economic and political climate. Table 2.1 summarizes how these missions address key science questions discussed above. The panel also provides a prioritized list of science goals and objectives for small missions or missions of opportunity.

Mission Priorities

The Inner Planets Panel's highest-ranked science missions are as follows:

1. *Mercury Science.* The successful implementation of the Messenger mission to Mercury, designed for the basic reconnaissance of Mercury's geology, atmosphere, magnetosphere, and topography, will finally complete our basic knowledge of the planets in the inner solar system. This is a long-standing high priority for exploration, and the panel reaffirms the strong community consensus for support. The panel explicitly reiterates the essential nature of the science objectives as being carried out by Messenger and expects full replacement in the event of unforeseen implementation problems.

2. *Venus In Situ Explorer (VISE).* The VISE mission is the highest-ranked new exploration mission for the inner planets. It is a detailed exploration and study of the composition of Venus's atmosphere and surface. Venus and Earth possibly had very similar surface conditions early in their histories, but Venus's subsequent evolution differed radically from that of Earth, developing an environment unsuitable for life. However, Venus is still a dynamic world with active geochemical cycles and nonequilibrium environments in the clouds and near surface that are not understood. VISE will make compositional and isotopic measurements of the atmosphere on descent

and of the surface on arrival at Venus. A core sample will be obtained at the surface and lofted to altitude, where further geochemical and mineralogical analyses will be made. In situ measurements of winds and radiometry will be obtained during descent, ascent, and at the balloon station. Scientific data obtained by this mission would help to constrain the history and stability of the Venus greenhouse and the recent geologic history, including resurfacing. The technology development achieved for this mission will pave the way for a potentially paradigm-altering sample-return mission in the following decade.

3. *South Pole-Aitken Basin Sample Return (SPA-SR).* The next highly ranked mission for inner solar system exploration is understanding basin-forming processes and impact chronology by returning samples from the South Pole-Aitken Basin on the farside of the Moon. The Moon provides a baseline for much of planetary science, and science questions associated with the Moon are at a high level of maturity. The South Pole-Aitken Basin is the largest known basin in the solar system and the oldest and deepest impact structure well preserved on the Moon (Figure 2.4). This giant basin allows access to materials from the interior of a small, differentiated planet. The SPA-SR mission will obtain samples of materials produced during this enormous impact event, enabling analysis

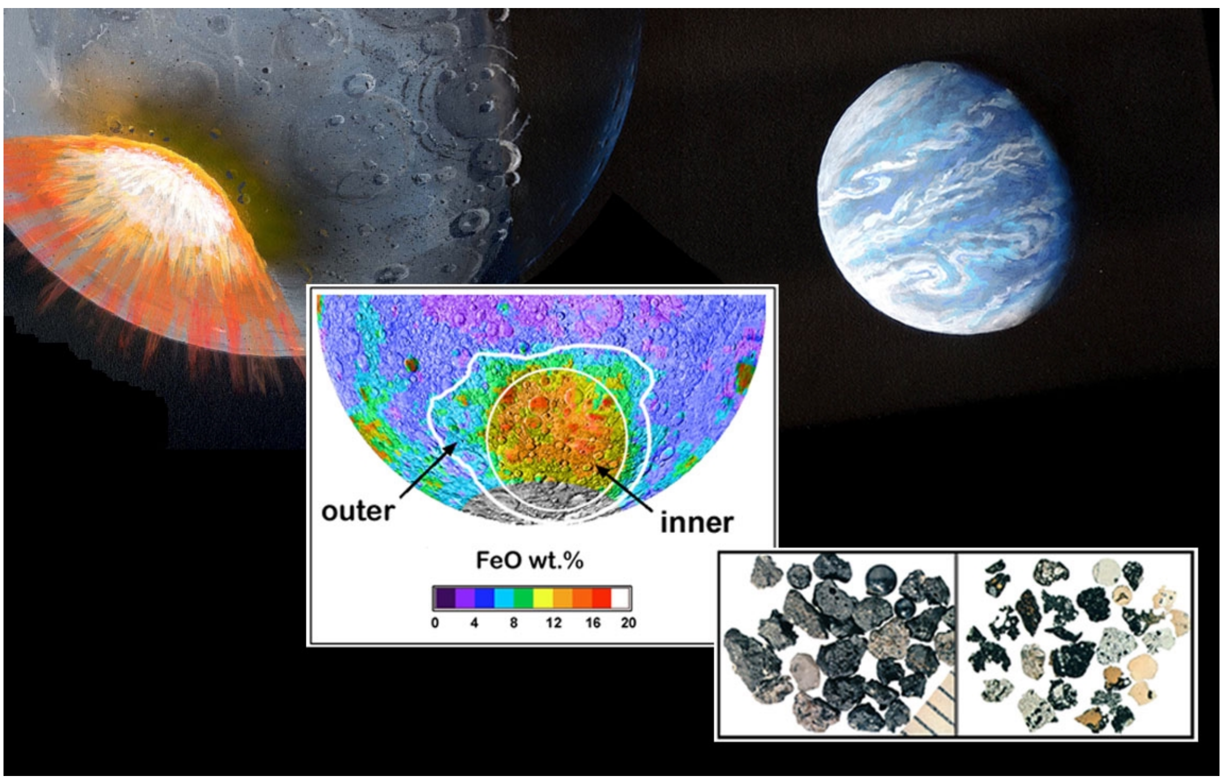

FIGURE 2.4 The Moon's South Pole-Aitken Basin at the moment of formation. A multi-ring basin formed as the initial cavity expanded and rim structures slumped into the growing depression. The SPA impact is expected to have excavated through the crust and into the upper mantle. The current basin interior remains distinctly FeO-rich, as determined from Clementine multispectral data (*middle image*). Lunar soils typically contain the diversity of representative rock types (*lower right*): note the millimeter scale. The date of SPA formation is not known, but early Earth was probably closer to the Moon than it is now, and may have been rotating faster (producing such cloud bands). Painting by W.K. Hartmann, 2002. Figures adapted from B.L. Jolliff, J.J. Gillis, L.A. Haskin, R.L. Korotev, and M.A. Wieczorek, "Major Lunar Crustal Terranes: Surface Expression and Crust-Mantle Origins," *Journal of Geophysical Research* 105: 4197-4216, 2000, and J.A. Wood, J.S. Dickey, U.B. Marvin, and B.N. Powell, "Lunar Anorthosites and a Geophysical Model of the Moon," in A.A. Levinson (ed.), *Proceedings of the Apollo 11 Lunar Science Conference Vol. 1*, Pergamon Press, New York, 1970, pp. 965-988.

TABLE 2.1 Summary of Priority Science Investigations Addressed by the Inner Planets Panel's Highest-Ranked Inner-Planet Missions

			Under Way	Near-term		Long-term	
Theme	Questions	Priority Science Investigations	**Mercury Messenger**	Venus In Situ Explorer	Moon SPA-SR[a]	**Venus Sample Return**	**Geophysical Network Science**
Past: What led to the unique character of our home planet?	a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?	1. Determine elemental and mineralogic surface compositions.	xxx	xxx	xxx	xxx	
		2. Measure noble gas composition of atmospheres.		xxx		xxx	
		3. Measure oxygen isotopic ratios of the unaltered surface and atmosphere.			x	xxx	
		4. Determine interior (mantle) compositions.			xxx	xxx	xx
	b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?	1. Determine horizontal and vertical variations in internal structures.	xxx		x		xxx
		2. Determine compositional variations and evolution of crusts and mantles.	xx	x	xxx	xxx	xx
		3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles.	xxx	x	xx	xx	xx
		4. Determine characteristics of Fe-rich metallic cores (size; liquid and solid components).	xx			xx	xxx
	c. What were the history and role of early impacts?	1. Determine large-impactor flux in the early solar system and calibrate the lunar impact record.			xxx	xxx	
		2. Determine the global geology of the inner planets.	xxx	xx	xx	xx	xx
		3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.	xx		xxx		xx
	d. What is the history of water and other volatiles and how did the atmospheres of inner planets evolve?	1. Make high-precision measurements of noble gases and light stable isotopes.		xxx		xxx	
		2. Determine the composition of magmatic volatiles.		x	x	xxx	
		3. Determine the composition and source of the polar deposits on Mercury and the Moon.	xx				
Present: What common dynamic processes shape Earth-like planets?	a. What processes stabilize climate?	1. Determine the general circulation and dynamics of the inner planets' atmospheres.		xx		xx	xxx
		2. Determine the composition of the atmospheres, especially trace gases and their isotopes.		xxx		xxx	
		3. Determine how sunlight, thermal radiation, and clouds drive greenhouse effects.		xx		x	xxx
		4. Determine processes and rates of surface/atmosphere interaction.		xxx		xxx	xx

	b. How do active internal processes shape the atmosphere and surface environments?	1. Characterize current volcanic and/or tectonic activity and outgassing.		xx			xxx
		2. Determine absolute ages of surfaces.			xx	xxx	
		3. Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium.	xxx				xx
	c. How do active external processes shape the atmosphere and surface environment?	1. Make precise compositional measurements of the surface-bounded atmospheres of Mercury and the Moon and determine the relationship between ionospheres and magnetospheres.	xxx				
		2. Quantify processes in the uppermost atmospheres of the terrestrial planets.	xxx	x			
		3. Quantify regolith processes on bodies with tenuous atmospheres.	x		x		
Future: What fate awaits Earth's environment and those of the other terrestrial planets?	a. What do the diverse climates of the inner planets reveal about the vulnerability of Earth's environment?	1. Characterize the greenhouse effect through meteorological observations.		xx		xx	xx
	b. How do varied geologic histories enable predictions of volcanic and tectonic activity?	1. Assess the distribution and age of volcanism on the terrestrial planets.	xx	x	x	xx	x
		2. Search for evidence of volcanic gases in inner planet atmospheres.		xxx		xxx	
	c. What are the consequences of impacting particles and large objects?	1. Determine the recent cratering history and current flux of impactors in the inner solar system.	xx		x	xx	xx
		2. Evaluate the temporal storage and record of solar-wind gases.		xx		xx	xx
	d. What are the resources of the inner solar system?	1. Assess volatile resources.	xx	xx		xx	x
		2. Assess mineral resources.	xx	xx	xx	xx	x

NOTE: The expected science returns from each of the missions shown are as follows: xxx = highly significant, xx = very useful, and x = supporting. Missions listed in boldface either are under way or are part of long-term planning.

[a]South Pole-Aitken Basin Sample Return mission.

of the effects of early, large impacts on the structure and evolution of the planets. Returned samples will include both soil and diverse rock chips.

Medium-Class Missions

Venus In Situ Explorer

The Inner Planets Panel's highest-ranked new mission for the next decade is the Venus In Situ Explorer (VISE). It would provide key measurements of the atmosphere and surface, as well as test technologies needed for a Venus surface and atmospheric sample-return mission in the subsequent decade.

Science measurement objectives of VISE are as follows:

- Determine the composition of Venus's atmosphere, including trace gas species and light stable isotopes;
- Accurately measure noble gas isotopic abundance in the atmosphere;
- Provide descent, surface, and ascent meteorological data;
- Measure zonal cloud-level winds over several Earth days;
- Obtain near-infrared descent images of the surface from 10-km altitude to the surface;
- Accurately measure elemental abundances and mineralogy of a core from the surface; and
- Evaluate the texture of surface materials to constrain weathering environment.

A Venus atmospheric and surface sample-return mission has been identified as the step in inner-planets exploration that is absolutely essential for determining why Venus has evolved such a different environment from that of Earth. This mission is complementary to the Mars surface sample-return mission, utilizing some common elements, such as an ascent capability and orbital rendezvous. However, several elements are unique to returning a sample from Venus and need to be demonstrated in situ. Development of these technologies will enable future sample-return and potential Discovery-class missions to Venus.

The key elements that will be tested by the Venus In Situ Explorer mission include the following:

- Aeroshell entry into Venus's atmosphere;
- Passive insulation and survival in the extreme environment of Venus;
- Sample acquisition and handling—a surface drill to obtain a sample quickly—for example, in less than 1 hour; and
- An ascent package that would loft the sample by balloon to an altitude of 70 km and survive for several Earth days.

Atmospheric Science Objectives. The composition of the lower atmosphere of Venus is unknown. Without this knowledge, comparisons of the factors that affect climate on Earth and on Venus, including photochemistry, clouds, volcanism, surface-atmosphere interactions, and the loss of light gases to space, are impossible. VISE will measure the abundance of trace gas species in the lower atmosphere of Venus to parts per million accuracy, enabling an understanding of how these processes affect terrestrial planetary climates. A fundamental quest is to understand how and why Venus, roughly the same size, composition, and distance from the Sun as Earth, has evolved to such a different state. The record of planetary atmospheres is contained in the isotope ratios of the most inert gases—xenon, krypton, argon, and neon. Are planetary atmospheres the remnants of gases that were originally solar in composition but then suffered massive hydrodynamic escape,[36] or did they acquire atmospheres from volatiles that had already been differentiated?[37] What was the role of impacts on the ultimate compositions and evolution of the terrestrial planets? Discrimination between these events for each of the inner planets is possible if noble gas isotopic ratios can be measured with a state-of-the-art neutral mass spectrometer. Previous spacecraft measurements have been inadequate to address these issues. VISE will determine the noble gas abundances and isotope ratios to sufficient accuracy to distinguish between hypotheses of the origin and evolution of Venus's atmosphere. A meteorological package will measure atmospheric pressure and temperature profiles down to the surface, and pressure, temperature, and winds at the surface. Cloud-level winds will be determined by tracking the ascent balloon during its 3.5-day lifetime, providing improved data on atmospheric dynamics and the origin of Venus's mysterious atmospheric superrotation.

Surface Science Objectives. The former Soviet Union's Venera landers returned basic elemental chemistry and images of four sites on the surface,[38-40] and Magellan data provided evidence of possible evolved volcanic deposits.[41] However, we lack sufficient information on surface elemental abundances and mineralogy to determine the degree of crustal evolution on Venus. The VISE mission would measure elemental compositions at a surface site complementary to those of the Veneras. Mineralogy of a surface sample core will be obtained for the first time, allowing analysis of any weathered layer and testing for depth of alteration and occurrence of unaltered material. Textural analysis of the sample using a microscope imaging system would provide information on the formation and nature of surface rocks. These data will be used to constrain questions outlined above. Despite global radar coverage of Venus by Magellan, little is known of the surface morphology at scales of 1 to 10 m. Without such information, it is difficult to determine how the plains formed and to understand the nature of mobile materials on the surface. A descent camera on the lander will provide the first broadscale visible images of the surface, with images returned from about 10 km altitude to the surface. These images will enhance interpretation of the Magellan radar images by providing ground-truth data on the surface texture of the lava flows that make up Venus's plains. The morphology and texture of these flows can be related to emplacement rate, volatile content, and rheology, which are needed in order to understand the role of volcanism in shaping the atmosphere and surface of Venus. Images of Venus's surface will also be returned from the lander, with filters chosen to provide compositional information. These images will help to determine the recent geologic history of Venus and will resolve differences in the interpretation of Venus's resurfacing history.[42]

Implementation. Science measurements will be made during three VISE mission phases: (1) the descent phase, with atmospheric experiments and descent imaging; (2) the landed phase, with surface imaging and atmospheric and surface chemistry; and (3) the ascent phase, with surface mineralogy and atmospheric circulation analysis. The panel stresses that VISE needs to be kept simple, with limited but focused objectives. The panel assumes that the instrument portion of the mission will be competed either as a package or individually.

Deep-atmosphere measurements should include these:

- A neutral mass spectrometer with an enrichment cell,
- A meteorological package that includes pressure and temperature sensors and wind-speed measurements at the surface, and
- Radio science investigations that track the ascent balloon, measuring cloud-level zonal winds.

Surface science experiments should include these:

- Near-infrared descent and lander cameras, with filters chosen to maximize surface-composition information;
- An instrument to measure the elemental geochemistry of a surface sample, likely an x-ray fluorescence analyzer or a new instrument utilizing technologies that are currently being developed. This measurement will be done inside the lander on the surface;
- An imaging microscope to analyze the core sample during ascent;
- An instrument to measure surface mineralogy. As this measurement requires time and benign conditions, it will occur at high altitude inside the ascent package; and
- Auxiliary experiments, such as a surface seismometer could be included, if mass margins and cost permit.

South Pole-Aitken Basin Sample Return

The return to Earth of rock fragments from the largest impact structure on the Moon, the South Pole-Aitken Basin, will address fundamental questions of inner solar system impact processes and chronology. Because these materials sample the deep interior, they would greatly increase our knowledge of the differentiation of planetary bodies and of the structure and composition of the Moon. Key measurements to be made on returned samples include radiometric ages of impact-melt rocks from the South Pole-Aitken Basin-forming event, and chemical, isotopic, and petrologic investigations of igneous and volcanic rocks from the deep crust and upper mantle of the Moon. This mission is considered a medium-class mission.

The SPA-SR mission will address fundamental issues relevant to the impact history of the inner planets and the Earth-Moon system and key remaining issues of lunar science. During Apollo, we sought to understand how a small planet sorts itself out—or differentiates—after its formation. What the Apollo and Luna missions—which investigated a limited region of the Moon's nearside—found was a considerably more complex planetary body than expected, and we have not really answered the question adequately. Remote-sensing results have recently provided the global context to address this issue as well as the effects of giant impacts in the early solar system.

Most models for the early evolution of the Moon include initial lunar differentiation forming segregated layers that are negatively buoyant and become gravitationally unstable, sinking toward the interior of the planet. Many aspects of the subsequent history, such as core formation and the generation of mare basalts, are linked to these events. Similar models have been proposed for Mars and Venus, and thus the characterization of the lower crust and upper mantle of the Moon will not only be a very significant step in distinguishing among several models for early lunar evolution, but it also will provide insight into processes that are likely to have occurred on other planets.

Solar System Science Objectives. The South Pole-Aitken Basin is the largest known structure of its type in the solar system and the oldest well-preserved basin on the Moon. Its age provides a key constraint on understanding basin-forming impact chronology throughout the solar system. Samples of materials produced by this enormous impact event will help decipher the following:

- Effects and timing of early, large impacts on planetary structure, differentiation, and orbital dynamics;
- The depth to which the impact penetrated (from sample composition and mineralogy); and
- The composition and origin of the impacting object (through trace-element and isotopic analyses).

Inner Solar System and Earth-Moon System Science Questions. Radiometric dating of samples of impact melt from the South Pole-Aitken Basin (and possibly from nearby smaller but later basins) will provide key evidence regarding the inner solar system and Earth-Moon system cratering chronology. The age of the South Pole-Aitken Basin will constrain the period of late, heavy bombardment and will provide a critical test of the hypothesis that the heavy bombardment was punctuated by a cataclysm, or spike, in the flux of large impactors. Understanding the bombardment flux is especially relevant for the Earth-Moon system and the evolution of early terrestrial environments.

Lunar Science Pivotal and Foundational Questions. The farside South Pole-Aitken Basin represents the principal major lunar terrain that remains unsampled.[43] Despite numerous subsequent smaller impacts, the enormous South Pole-Aitken Basin retains its distinct regional geochemical anomaly, observed remotely in FeO and thorium concentrations.[44,45] Recent remotely sensed information further suggests that the floor of the basin may largely represent the mineralogy of the Moon's lower crust, although impact breccias could contain mantle rocks as clasts (and mantle rocks may be distributed within the regolith).[46-48] Analysis of materials from the basin thus is expected to provide key information regarding fundamental problems of the present-day surface of the Moon and its geologic history, including the following:

- Composition and mineralogy of the lower crust determined directly from samples, allowing testing of models for the differentiation of the Moon's crust and mantle;
- Composition and mineralogy of the mantle (potential rocks or clasts in breccia would be the first direct samples of the lunar mantle);
- Ancient materials from the lunar farside that are not biased by the nearside impact basins, which dominate current Apollo and Luna samples;

• Validation of compositional remote sensing over a major region of the Moon for which no representative samples are known to exist in Apollo, Luna, or meteorite collections, and where existing data are ambiguous or otherwise not well understood (enabling improved determination of bulk composition);

• Sources of observed anomalous concentrations of thorium and other heat-producing elements to understand lunar differentiation and thermal evolution, including volcanism. This also addresses the origin of global planetary asymmetry and whether Th is enriched in the Moon relative to Earth, which is important for understanding the origin of the Moon from an early giant impact into the Earth; and

• Ages and compositions of farside basalts to determine how mantle source regions on the farside of the Moon differ from regions sampled by Apollo and Luna basalts.

From experience with Apollo regolith samples and because of the efficiency of lateral and vertical mixing, a diversity of rock samples is expected in a representative sample from well-selected sites within SPA.

Implementation. The SPA-SR mission concept includes a robotic lander with automated scooping and sieving capability to enhance the return of rock fragments along with bulk regolith. A kilogram of returned mature lunar soil without sieving would be expected to include some 5,000 rock fragments in the 1- to 10-mm range. To maximize the likelihood of obtaining a sample of original SPA basin impact-melt rocks and other desired materials, a roving capability or a multiple (three) lander concept could be employed. If multiple landers were incorporated, important lunar geophysical network science could be obtained to provide a structural context for the basin and the returned samples. The mission would include descent imaging to provide geologic context. A relay satellite is also required for command and control and to enable extended network science. This mission would serve as a testbed for key technology development associated with automated sampling, encapsulation, and return to Earth.

Discovery and Small-Class Missions

Summarized below are science objectives that could likely be met within or below the Discovery cost caps for the inner planets. These relate to objectives that can be achieved within the R&A program (Earth-based facilities), as missions of opportunity, or in collaboration with foreign investigations, or as peer-reviewed Discovery missions. The panel provides a list of such prioritized objectives for Mercury, Venus, and the Moon.

Mercury Science

The following investigations can be addressed by Earth-orbiting and/or ground-based telescopes or by Discovery missions that are complementary to Messenger:

• Investigate high-latitude volatiles to verify deposits (composition, extent, depth), to determine sources (solar wind, cometary, meteoritic) and history (recent versus ancient), and to understand the deposition process.

• Acquire a complete mineralogical map of the surface to understand variations among the terrestrial planets in crustal formation and surface evolution.

• Analyze the morphology and stability of the magnetosphere by measuring the intensity and distribution of ionic species emissions from beyond Mercury's orbit. This provides an opportunity to observe active space weather before it reaches Earth.

• Study the morphology of the neutral atmospheric species to determine if they are provided from surface materials, the interplanetary medium, meteoritic flux, endogenic sources, or a combination of these.

Significant technological advances or innovative approaches will be necessary in order for the following objectives to fit within an augmented Discovery-class mission:

• Return a sample from the surface to place Mercury in the context of solar system chemistry, determine volcanic and thermal history, and calibrate the crater flux (age dating).

• Emplace a geophysical network (seismic, heat flow) to determine internal structure, distribution of heat-producing elements, lateral and vertical heterogeneity of crust and mantle, and the true density of the core. Geophysical network science would address how small bodies differentiate and how the bulk composition of Mercury is related to the composition of the terrestrial planets.

Venus Science

Some of the following objectives can be addressed, either alone or combined with others, by new Discovery missions; some will be addressed by missions of the European Space Agency (ESA) and Japan's Institute of Space and Astronautical Science (ISAS); and others can be addressed by ground- or space-based observing programs.

• Lower-atmosphere trace gases and dynamics. Information is needed on how trace species vary over time and space and how they participate in cloud-forming processes, thermochemical reactions, and reactions with surface minerals. Such observations (e.g., by an advanced infrared imaging spectrometer) can also be used to look for direct evidence of extant volcanism.

• Monitoring global geological processes, such as volcanism, tectonics, and mass wasting, by imagery and topography with horizontal resolution in the few tens-of-meters range. Techniques are available for detecting changes on planetary surfaces (e.g., inflation of active volcanoes before eruptions) on centimeter scales.

• Exospheric mass loss and thermospheric dynamics. A suite of instruments can operate from Venus orbit or from HST and JWST to measure the loss of light species from Venus's atmosphere (this is key to understanding how Venus evolved to a state so different from that of Earth).

• Geothermal heat flow measured at multiple locations to determine rates of heat flow within the planet and between the surface and atmosphere and to lead to better understanding of volcanism and tectonics of the crust and mantle. (This objective will likely require significant technology development.)

• Measurement of middle-atmosphere trace gases and dynamics (by submillimeter heterodyne technology and direct Doppler wind measurements).

The following objectives may be moved into the Discovery class with technologies developed for VISE:

• Visual reconnaissance of the surface below the clouds to provide important ground-truth for Magellan radar images and far more refined geological interpretation of the surface;

• Global atmospheric dynamics explored in detail with long-lived instruments (e.g., on a fleet of balloons), including in situ pressure and temperature measurements, and possibly also direct measurements of solar and thermal radiation;

• Noble-gas and trace species measurements made with a simple Venus atmosphere sample-return mission. Such measurements are essential for understanding the origin and evolution of Venus's atmosphere (and for comparisons with Earth). Analyses on Earth would then be performed that would allow the measurement of noble and trace gas species to many orders higher precision than has been done for any planet other than Earth.

Lunar Science

New Discovery-class missions can address most of the following objectives wholly or in part. Several are planned to be addressed by European and Japanese lunar missions that are scheduled for launch within the next 5 years and will provide valuable opportunities for U.S. participation.

• Geophysical network science (seismic, heat flow) to determine internal structure, distribution of heat-producing elements, lateral and vertical heterogeneity of crust and mantle, and the possible existence of an iron-rich core. Geophysical network science would address how small planetary bodies differentiate, how the bulk composition of the Moon is related to the composition of Earth, and how planetary compositions are related to nebular condensation and planetary accretion processes (the Japanese Lunar-A mission contains two such instrumented penetrators);

• Investigation of the extended history of basaltic volcanism and calibration of the impact flux by returning a sample from the youngest lunar lavas (e.g., Lichtenberg-Rümker Hills). This would also address why basalts formed where they did in space and time (e.g., nearside-farside dichotomy and origin/evolution of the Procellarum region), and how the Moon cooled generally;

• Investigation of polar volatiles to verify deposits (character, mineralogy, composition, extent, depth), to determine sources (solar wind, cometary, meteorite) and history (recent versus ancient), and to understand processes of volatile migration and deposition on airless bodies;

• Determination of topography at high resolution (hundreds of meters to kilometers), as done by the Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor, in order to carry out detailed geologic investigations as well as to address the geophysical properties of the Moon's crust and mantle and the Moon's thermal evolution from hot and weak to cold and rigid;

• Determination and mapping of the mineral composition of the surface (through hyperspectral imaging) at sufficient spatial resolution to advance understanding of the petrologic relationships within and the origins of principal geologic units;

• Targeted area studies to understand impact chronology, especially the post-3 Gyr flux history and spikes or other periodicity in the impact flux (accomplished by age-dating key stratigraphic units and impact-crater melt rocks with returned samples);

• Determining the major-element composition of the surface of the Moon (including magnesium, aluminum, and calcium and other measurable elements at improved resolution compared with existing data) in order to better characterize the distribution of materials on the lunar surface and to understand the formation, differentiation, and bulk composition of the Moon;

• Stereo imaging coverage for high-resolution (e.g., 10 m), three-dimensional definition of geology and surface morphology to address local and regional issues (geologic interpretation, resource evaluation, Moon-base planning); and

• Geological site characterization in order to derive the geological evolution of the surface at key locations and to deconvolve the interplay between tectonic, impact, and volcanic processes (e.g., extended/long-duration rover traverse, imaging, and in situ analysis).

A Long-Term Exploration Strategy for the Inner Planets

The inner solar system affords the opportunity to address broad objectives for understanding the history, current state, and potential future of habitable planets. The Inner Planets Panel's strategy is to focus on the highest-priority science objectives for Mercury, Venus, and the Moon in the decade 2003-2013. Exploration efforts in the subsequent decade should focus on the return of samples from Venus and Mercury and on essential network science. The latter involves the establishment of multiple surface stations operating concurrently on a planet, and are referred to as "Geophysical Network Science" in Table 2.1. Missions to implement these networks would involve individual projects for Mercury, Venus, and the Moon. Because of the challenges posed by network science and, in particular, sample-return missions, it is critical that key technologies be developed and proven in order to enable their implementation. Thus, a second-order aspect of the Venus In Situ Explorer mission includes developing technologies for obtaining samples and lifting them from the surface. This technology will draw on heritage currently being established for the Mars sample-return program. It should be noted that a Venus sample-return mission, perhaps the highest-priority mission for inner planet exploration in the subsequent decade, is the only way to accomplish the following:

• Measure the isotopic composition of oxygen, to provide crucial information on this important characteristic of solar system formational processes;

• Obtain the isotopic composition of certain elements (e.g., Nd, W, Hf, Sr, Pb, Os, for which specific isotopes are products of radiogenic decay), to address the timing and extent of metallic core formation, the timing and extent of mantle differentiation, and the depth, mineralogy, and chemical composition of source regions for these basalts; and

- Determine the age of returned rocks, to constrain the geologic history of Venus and allow comparison with the Earth.

Not all of the fundamental science issues for the inner planets can be addressed by the priority missions proposed here. However, as discussed earlier, substantial advances must be made in understanding how planets work, and much can be achieved through one or more focused Discovery-class missions. In addition, an integral part of the exploration of the inner planets is the integration of data analysis, supporting research, technology development, and education and public outreach programs with flight projects. For example, establishment of sample receiving facilities and the laboratories for the analysis of extraterrestrial materials must be in place well before the return of samples. Although such capabilities are likely to be implemented within the context of the Mars Exploration Program, plans must accommodate non-martian materials. Similarly, R&A supporting facilities and studies of planetary processes (e.g., laboratory, field-analog, computer modeling) must be supported sufficiently to enable both planning and scientific validation of results from flight projects. Most importantly, robust data analysis programs are essential to harvest the investment made with flight programs. Ground-based observations are expected to continue to make major contributions to monitoring atmospheric changes and mapping.

In conclusion, the inner planets hold fundamental clues to the development of Earth-like planets in our solar system and elsewhere. They provide valuable insights into the paths toward and stability of habitable environments. The most fundamental questions about these planets, such as their nature, their compositions, the interactions of their surfaces and atmospheres, and the role of impacting objects, will be addressed by the missions recommended here.

REFERENCES

1. S.R. Taylor, *Solar System Evolution: A New Perspective*, Cambridge University Press, New York, 2001.
2. F. Robert, "The Origin of Water on Earth (Perspectives)," *Science* 293: 1056-1058, 2001.
3. M.A. Wieczorek and R.J. Phillips, "Potential Anomalies on a Sphere: Applications to the Thickness of the Lunar Crust," *Journal of Geophysical Research* 103: 1715-1724, 1998.
4. M.A. Wieczorek and R.J. Phillips, "The Procellarum KREEP Terrane: Implications for Mare Volcanism and Lunar Evolution," *Journal of Geophysical Research* 105: 20417-20430, 2000.
5. L.L. Hood and M.T. Zuber, "Recent Refinements in Geophysical Constraints on Lunar Origin and Evolution, " in *Origin of the Earth and Moon*, University of Arizona Press, Tucson, 2000, pp. 397-409.
6. R.J. Phillips and V.L. Hansen, "Tectonic and Magmatic Evolution of Venus," *Annual Reviews of Earth and Planetary Science* 22: 597-654, 1994.
7. R.G. Strom, G.G. Schaber, and D.D. Dawson, "The Global Resurfacing of Venus," *Journal of Geophysical Research* 99: 10899-10926, 1994.
8. W.K. Hartmann, G. Ryder, L. Dones, D. Grinspoon, "The Time-Dependent Intense Bombardment of the Primordial Earth/Moon System," in R. Canup and K. Righter (eds.), *Origin of the Earth and Moon*, University of Arizona Press, Tucson, 2000, pp. 493-512.
9. W.B. McKinnon, K.J. Zahnle, B.A Ivanov, and H.J. Melosh, "Cratering on Venus: Models and Observations," in S.W. Bougher, D.M. Hunten, and R.J. Phillips (eds.), *Venus II*, University of Arizona Press, Tucson, 1997, pp. 969-1014.
10. S.A. Stern, "The Lunar Atmosphere: History, Status, Current Problems, and Context," *Reviews of Geophysics* 37: 453-491, 1999.
11. B. Butler, D. Muhleman, and M. Slade, "Mercury: Full-Disk Radar Images and the Detection and Stability of Ice at the North Pole," *Journal of Geophysical Research* 98: 15003-15023, 1993.
12. L.W. Esposito, R.G. Knollenberg, M.Y. Marov, O.B. Toon, and R.P. Turco, "The Clouds and Hazes of Venus," in D.M. Hunten, L. Colin, T.M. Donahue, and V.I. Moroz (eds.), *Venus*, University of Arizona Press, Tucson, 1983, pp. 484-564.
13. P.B. James, H.H. Kieffer, and D.A. Paige, "The Seasonal Cycle of Carbon Dioxide on Mars," in H.H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews (eds.), *Mars*, University of Arizona Press, Tucson, 1992, pp. 934-968.
14. See, for example, D.M. Hunten, T.M. Donahue, J.C.G. Walker, and J.F. Kasting, "Escape of Atmospheres and Loss of Water," in S.K. Atreya, J.B. Pollack, and M.S. Matthews (eds.), *Origin and Evolution of Planetary and Satellite Atmospheres*, University of Arizona Press, Tucson, 1989, pp. 386-422.
15. D.J. Stevenson, "Planetary Science—A Space Odyssey," *Science* 287: 997-1005, 2000.
16. D.M. Williams and D. Pollard, "Earth-Moon Interactions: Implications for Terrestrial Climate and Life," in R. Canup and K. Righter (eds.), *Origin of the Earth and Moon*, University of Arizona Press,Tucson, 2000, pp. 513-525.
17. A.T. Basilevsky, J.W. Head, G.G. Schaber, G.G. Strom, and R.G. Strom, "The Resurfacing History of Venus," in S.W. Brougher, D.M. Hunten, and R.J. Phillips (eds.), *Venus II*, University of Arizona Press, Tucson, 1997, pp. 1047-1085.

18. N.F. Ness, "Mercury: Magnetic Field and Interior," *Physics of Earth and Planetary Interiors* 20: 204-217, 1978.

19. M.H. Acuña, J.E.P. Connerney, P. Wasilewski, R.P. Lin, D. Mitchell, K.A. Anderson, C.W. Carlson, J. McFadden, H. Rème, C. Mazelle, D. Vignes, S.J. Bauer, P. Cloutier, and N.F. Ness, "Magnetic Field of Mars: Summary of Results from the Aerobraking and Mapping Orbits," *Journal of Geophysical Research* 106: 23403-23418, 2001.

20. R.J. Phillips, M.T. Zuber, S.C. Solomon, M.P. Golombek, B.M. Jakosky, W.B. Banerdt, D.E. Smith, R.M.E. Williams, B.M. Hynek, O. Aharonson, and S.A. Hauck, "Ancient Geodynamics and Global-Scale Hydrology on Mars," *Science* 291: 2587-2591, 2001.

21. See, for example, S.A. Stern, "The Lunar Atmosphere: History, Status, Current Problems, and Context," *Reviews of Geophysics* 37: 453-491, 1999.

22. C.M. Pieters, J.W. Head III, L. Gaddis, B. Jolliff, and M. Duke, "Rock Types of South Pole-Aitken Basin and Extent of Basaltic Volcanism," *Journal of Geophysical Research* 106: 28001-28022, 2001.

23. B. Hapke, "Space Weathering from Mercury to the Asteroid Belt," *Journal of Geophysical Research* 106: 10039-10074, 2001.

24. P.F. Hoffman, A.J. Kaufman, G.P. Halverson, and D.P. Schrag, "A Neoproterozoic Snowball Earth," *Science* 281: 1342-1346, 1998.

25. J.F. Kasting and O.B. Toon, "Climate Evolution on the Terrestrial Planets," in S.K. Atreya, J.B. Pollack, and M.S. Matthews (eds.), *Origin and Evolution of Planetary and Satellite Atmospheres*, University of Arizona Press, Tucson, 1989, pp. 423-449.

26. J.B. Pollack, "Kuiper Prize Lecture: Present and Past Climates of the Terrestrial Planets," *Icarus* 91: 173-198, 1991.

27. M.A. Bullock and D.H. Grinspoon, "The Recent Evolution of Climate on Venus," *Icarus* 150: 19-37, 2001.

28. H. Hiesinger, R. Jaumann, G. Neukum, and J.W. Head III, "Ages of Mare Basalts on the Lunar Nearside," *Journal of Geophysical Research* 105: 29239-29275, 2001.

29. E.M. Shoemaker, "Long-Term Variations in the Impact Cratering Record on Earth," in M.M. Grady, R. Hutchison, G.J.H. McCall, and D.A. Rothery (eds.), *Meteorites: Flux with Time and Impact Effects*, Geological Society of London Special Publications 140: 7-10, 1998.

30. W.C. Feldman, S. Maurice, D.J. Lawrence, R.C. Little, S.L. Lawson, O. Gasnault, R.C. Wiens, B.L. Barraclough, R.C. Elphic, T.H. Prettyman, J.T. Steinberg, and A.B. Binder, "Evidence for Water Ice Near the Lunar Poles," *Journal of Geophysical Research* 106: 23231-23252, 2001.

31. G.L. Kulcinski, "Using Lunar Helium-3 to Generate Nuclear Power Without the Production of Nuclear Waste," 20th International Space Development Conference, Albuquerque, N. Mex., May 24-28, 2001.

32. G.W. Wetherill, "The Formation and Habitability of Extrasolar Planets," *Icarus* 119: 219-238, 1996.

33. S.R.Taylor, "On the Difficulties of Forming Earth-like Planets," *Meteoritics and Planetary Science* 34: 317-329, 1999.

34. L. Wilson and K. Keil, "Volcanic Eruptions and Intrusions on the Asteroid 4 Vesta," *Journal of Geophysical Research* 101: 18927-18940, 1996.

35. M.J. Drake, "The Eucrite/Vesta Story," *Meteoritics and Planetary Science* 36: 501-513, 2001.

36. R.O. Pepin, "Evolution of Earth's Noble Gases: Consequences of Assuming Hydrodynamic Loss Driven by Giant Impact," *Icarus* 125: 148-156, 1997.

37. K. Zahnle, J.B. Pollack, and J.F. Kasting, "Xenon Fractionation in Porous Planetesimals," *Geochimica et Cosmochimica Acta* 54: 2577-2586, 1990.

38. Y.A. Surkov, V.L. Barsukov, L.P. Moskalyeva, V.P. Kharyukova, and A.L. Kemurdzhian, "New Data on the Composition, Structure and Properties of Venus Rock Obtained by Venera 13 and Venera 14," in *Proceedings of the 14th Lunar and Planetary Science Conference*, *Journal of Geophysical Research Supplement* 89: B393-B402, 1984.

39. Y.A. Surkov, L.P. Moskalyeva, V.P. Kharyukova, A.D. Dudin, G.G. Smirnov, and S.Y. Zaitseva, "Venus Rock Composition at the Vega 2 Landing Site," in *Proceedings of the 17th Lunar and Planetary Science Conference Part 1*, *Journal of Geophysical Research* 91: E215-E218, 1986.

40. V.L. Barsukov, Y.A. Surkov, L.V. Dimitriyev, and I.L. Khodakovsky, "Geochemical Studies on Venus with the Landers from the Vega 1 and Vega 2 Probes," *Geochemistry International* 23: 53-65, 1986.

41. H.J. Moore, J.J. Plaut, P.M. Schenk, and J.W. Head, "An Unusual Volcano on Venus," *Journal of Geophysical Research* 97: 13479-13494, 1992.

42. See, for example, A.T. Basilevsky, J.W. Head, G.G. Schaber, G.G. Strom, and R.G. Strom, "The Resurfacing History of Venus," in S.W. Brougher, D.M. Hunten, and R.J. Phillips (eds.), *Venus II*, University of Arizona Press, Tucson, 1997, pp. 1047-1085; or J.E. Guest and E.R. Stofan, "A New View of the Stratigraphic History of Venus," *Icarus* 139: 55-66, 1999.

43. See, for example, B.L. Jolliff, J.J. Gillis, L.A. Haskin, R.L. Korotev, and M.A. Wieczorek, "Major Lunar Crustal Terranes: Surface Expressions and Crust-Mantle Origins," *Journal of Geophysical Research* 105 (E2): 4197-4216, 2000.

44. D.J. Lawrence, W.C. Feldman, B.L. Barraclough, A.B. Binder, R.C. Elphic, S. Maurice, and D.R. Thomsen, "Global Elemental Maps of the Moon: The Lunar Prospector Gamma-Ray Spectrometer," *Science* 281: 1484-1489, 1998.

45. D.J. Lawrence, W.C. Feldman, B.L. Barraclough, A.B. Binder, R.C. Elphic, S. Maurice, M.C. Miller, and T.H. Prettyman, "Thorium Abundances on the Lunar Surface," *Journal of Geophysical Research* 105 (E8): 20307-20331, 2000.

46. C.M. Pieters, S. Tompkins, J.W. Head III, P.C. Hess, "Mineralogy of the Mafic Anomaly in the South Pole-Aitken Basin: Implications for Excavation of the Lunar Mantle," *Geophysical Research Letters* 24: 1903, 1997.

47. C.M. Pieters, J.W. Head III, L. Gaddis, B. Jolliff, and M. Duke, "Rock Types of South Pole-Aitken Basin and Extent of Basaltic Volcanism," *Journal of Geophysical Research* 106 (E11): 28001-28022, 2001.

48. P.G. Lucey, G.J. Taylor, B.R. Hawke, and P.D. Spudis, "FeO and TiO_2 Concentrations in the South Pole-Aitken Basin: Implications for Mantle Composition and Basin Formation," *Journal of Geophysical Research* 103 (E2): 3701-3708, 1998.